# Search for the pentaquark candidate $\Theta(1540)^+$ in the hyperon beam experiment WA89

M.I. Adamovich,[1,a] Yu.A. Alexandrov,[1,b] S.P. Baranov,[1] D. Barberis,[2] M. Beck,[3] C. Bérat,[4] W. Beusch,[5] M. Boss,[6] S. Brons,[3,c] W. Brückner,[3] M. Buénerd,[4] C. Busch,[6] C. Büscher,[3] F. Charignon,[4] J. Chauvin,[4] E.A. Chudakov,[6,d] U. Dersch,[3] F. Dropmann,[3] J. Engelfried,[6,e] F. Faller,[6,f] A. Fournier,[4] S.G. Gerassimov,[3,1,g] M. Godbersen,[3] P. Grafström,[5] Th. Haller,[3] M. Heidrich,[3] E. Hubbard,[3] R.B. Hurst,[2] K. Königsmann,[3,g] I. Konorov,[3,1,h] N. Keller,[6] K. Martens,[6,i] Ph. Martin,[4] S. Masciocchi,[3,j] R. Michaels,[3,d] U. Müller,[7] H. Neeb,[3] D. Newbold,[8] C. Newsom,[9] S. Paul,[3,h] J. Pochodzalla,[3,k] I. Potashnikova,[3] B. Povh,[3] R. Ransome,[10] Z. Ren,[3] M. Rey-Campagnolle,[4,l] G. Rosner,[7,m] L. Rossi,[2] H. Rudolph,[7] C. Scheel,[11] L. Schmitt,[7,h] H.-W. Siebert,[6,n] A. Simon,[6,g] V.J. Smith,[8,o] O. Thilmann,[6] A. Trombini,[3] E. Vesin,[4] B. Volkemer,[7] K. Vorwalter,[3] Th. Walcher,[7] G. Wälder,[6] R. Werding,[3] E. Wittmann,[3] and M.V. Zavertyaev[1,b]

(WA89 collaboration)

[1] *Moscow Lebedev Physics Institute, RU-117924, Moscow, Russia*
[2] *Genoa University/INFN, Dipartimento di Fisica,I-16146 Genova, Italy*
[3] *Max-Planck-Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany*
[4] *Grenoble ISN, F-38026 Grenoble, France*
[5] *CERN, CH-1211 Genève 23, Switzerland*
[6] *Universität Heidelberg, Physikalisches Institut, D-69120 Heidelberg, Germany*[p]
[7] *Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany*[q]
[8] *University of Bristol, Bristol, United Kingdom*
[9] *University of Iowa, Iowa City, IA 52242, USA*
[10] *Rutgers University, Piscataway, New Jersey 08854, USA*
[11] *NIKHEF, 1009 D8 Amsterdam, The Netherlands*

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We report on a high-statistics search for the $\Theta(1540)^+$ resonance in $\Sigma^-$-nucleus collisions at 340 GeV/$c$ . No evidence for this resonance was found in our data sample which contains 13 millions $K_s^0 \to \pi^+\pi^-$ decays above background. For the decay channel $\Theta^+ \to K_s^0 p$ and the kinematic range $x_F > 0.05$ we find the production cross section to be $BR(\Theta^+ \to K_s^0 p) \cdot \sigma_0 < 1.8$ $\mu$b per nucleon at 99% CL.

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During the last years twelve experimental groups have reported evidence for a narrow baryonic resonance in the KN channel at a mass of about 1540 MeV/$c^2$ [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Figure 1 shows a collection of the first nine published results which gave evidence for the existence of the so called $\Theta(1540)^+$. While the number of positive observations seems to be quite convincing, when plotting the data points with error bars but without background curves to guide the eye it becomes obvious that the limited statistics is a common drawback of the individual observations. It is remarkable that the event statistics is nearly independent of the experimental situation and it is disturbing that the peak positions differ significantly in the various experiments. On the other hand at least 11 experiments have reported negative search results [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. It was

[a] Deceased.
[b] Supported by the Deutsche Forschungsgemeinschaft, contract number436 RUS 113/465, and Russian Foundation for Basic Research under contract number RFFI 98-02-04096.
[c] Present address: TRIUMF, Vancouver, B.C., Canada V6T 2A3
[d] Present address: Thomas Jefferson Lab, Newport News, VA 23606, USA.
[e] Present address: Institudo de Fisica, Universidad San Luis Potosi, S.L.P. 78240, Mexico.
[f] Present address: Fraunhofer Institut für Solarenergiesysteme, D-79100 Freiburg, Germany.
[g] Present address: Fakultät für Physik, Universität Freiburg, Germany.
[h] Present address: Technische Universität München, Garching, Germany.
[i] Present address: Department of Physics and Astronomy, SUNY at Stony Brook, NY 11794-3800, USA.
[j] Present address: Max-Planck-Institut für Physik, München, Germany.
[k] Contact person:pochodza@kph.uni-mainz.de; present address: Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany.
[l] Present address: CERN, CH-1211 Genève 23, Switzerland
[m] Present address: Dept. of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[n] Present address: Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany.
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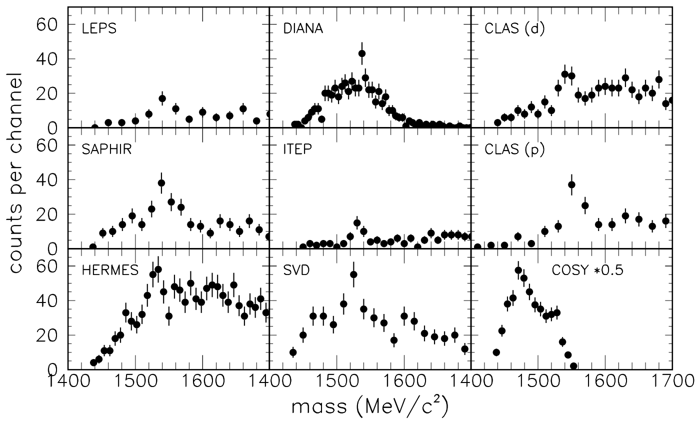


FIG. 1: *Summary of the first nine published observations of the* $\Theta(1540)^+$ *resonance [1, 2, 3, 4, 5, 6, 7, 8, 9].*

argued that this discrepancy may be due to very different production cross sections in the various reaction processes (see e.g. Refs. [24, 25, 26, 27, 28, 29]). Facing such a situation, further high statistics searches for this resonance under different experimental conditions – e.g. different beam particles – are highly desirable.

The hyperon beam experiment WA89 at CERN ran from 1990 to 1994 in the West Hall. Its primary goal was the study of charmed particles and their decays. At the same time it collected a high statistics data sample of hyperons and hyperon resonances, among these $\Lambda$ decays, and also $K_s^0$ decays. We have already published the negative result of a search for the pentaquark candidate $\Phi(1860)$ , alternatively called $\Xi(1860)^{--}$ [30]. Here we report a search for the pentaquark candidate $\Theta(1540)^+$ in the $K_s^0 p$ decay channel, produced inclusively in $\Sigma^-$-nucleus reactions. The results are based on the data collected in the years 1993 and 1994.

The hyperon beamline selected negatively charged particles with a mean momentum of 340 GeV/$c$ and a momentum spread of $\sigma(p)/p = 9\%$. At the experimental target, the $\pi^-$ to $\Sigma^-$ ratio of the beam was about 2.3. The beam pions were strongly suppressed at the trigger level by a set of transition radiation detectors resulting in a remaining pion contamination of about 12%. In addition the beam contained small admixtures of $K^-$ and $\Xi^-$. The experimental target itself consisted of one copper slab with a thickness of 0.025 $\lambda_I$ in beam direction, followed by three carbon (diamond powder) slabs of 0.008 $\lambda_I$ each. The trajectories of incoming and outgoing particles were measured in silicon microstrip detectors upstream and downstream of the targets. Only events with a reconstructed interaction vertex in the targets and the surrounding counters were retained in the analysis.

The momenta of charged particles were measured in a magnetic spectrometer equipped with MWPCs and drift chambers. The spectrometer magnet was placed with its center 13.6 m downstream of the target, thus providing a field-free decay zone of about 10m length for hyperons and $K_s^0$ emerging from the target.

A ring-imaging Cherenkov counter placed downstream of the spectrometer magnet provided particle identification. It was followed by a leadglass electromagnetic calorimeter and an iron/scintillator hadron calorimeter, which were not used in this analysis.

$K_s^0$ were reconstructed in the decay $K_s^0 \to \pi^+\pi^-$, using all pairs of positive and negative particles which formed a decay vertex in the decay zone. $\Lambda \to p\pi^-$ decays with decay particle momenta corresponding to $K_s^0 \to \pi^+\pi^-$ decays can produce a spurious mass peak at 1540 MeV/$c^2$, if a mirror image of the decay proton is used in the search for $K_s^0 p$ decays [14, 31]. To avoid this, we excluded $K_s^0$ candidates with a reconstructed $p\pi^-$ mass within $\pm 2\,\sigma_m(\Lambda)$ of the $\Lambda$ mass ($\sigma_m(\Lambda)$ was 1.8 MeV/$c^2$ at low momenta and 2.8 MeV/$c^2$ at 200 GeV/$c$). This requirement reduced the $K_s^0$ sample by 3% and the background by 1/3.

The reconstructed $\pi^+\pi^-$ mass distribution of the remaining $K_s^0$ candidates is shown in fig. 2. The peak from $K_s^0$ decays contains about 13 million events, their momentum spectrum extends from 10 GeV/$c$ to about 200 GeV/$c$. Above this momentum, very few $K_s^0$ are left, and they do not contribute to $K_s^0 p$ effective masses below 1570 MeV/$c^2$. The mass resolution is $\sigma_m(K_s^0)$ = 4 MeV/$c^2$ at low momenta and increases to $\sigma_m(K_s^0)$ = 7 MeV/$c^2$ at 200 GeV/$c$. Candidates with a reconstructed $\pi^+\pi^-$ mass within $\pm 2\,\sigma_m$ of the $K_s^0$ mass were retained for further analysis.

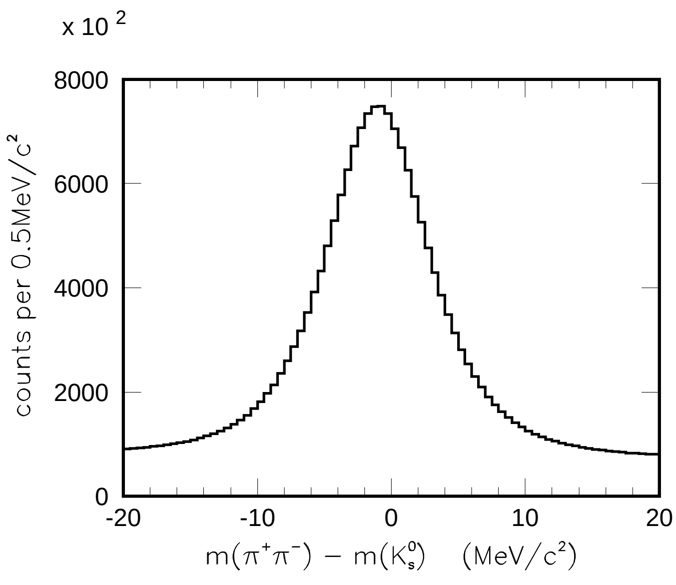


FIG. 2: Reconstructed mass distribution m($\pi^+\pi^-$) - m($K_s^0$) of $K_s^0$ candidates.

All positive particles with a reconstructed track extending from the microstrip counters downstream of the target to the wire chambers beyond the spectrometer were considered as proton candidates, excluding of course the $\pi^+$ from the $K_s^0$ decay. Requiring track reconstruction in the microstrip counters rejected most of the pro-

tons from $\Lambda$ decays. The track had to be inside the acceptance of the RICH counter, which implies a momentum threshold at around 12 GeV/$c$. Since the proton threshold of the RICH was at 38 GeV/$c$ we did not require proton identification, but rejected clearly identified $\pi^+$ and $K^+$ (thresholds at 5.5 and 20 GeV/$c$, resp.). From a study of reconstructed $\Lambda$ decays, we determined that this requirement rejected 4% or less of genuine protons at all momenta, while the $K^0_s p$ candidate sample was reduced by a factor of 3.

The final $K^0_s p$ sample contained 5.2 million $K^0_s p$ candidates. Fig. 3 shows the $K^0_s p$ mass distribution of all candidates up to 2 GeV. No narrow signal is visible in this plot, neither did we see narrow signals around an invariant mass of 1540 MeV/$c^2$ in subsamples of $x_F$ or transverse momentum $p_t$ [32]. We define $x_F$ as $x_F = 2p^*_L/\sqrt{s}$, where $p^*_L$ is the $K^0_s p$ momentum component in beam direction in the beam-nucleon CMS and $\sqrt{s}$ is the invariant mass of the beam-nucleon system. In our case, $\sqrt{s} = 25.2$ GeV. The $x_F$ distribution is shown in fig. 4 for the $K^0_s p$ mass region between 1500 and 1560 MeV/$c^2$, it starts at $x_F = 0.05$ and thus covers part of the central production region.

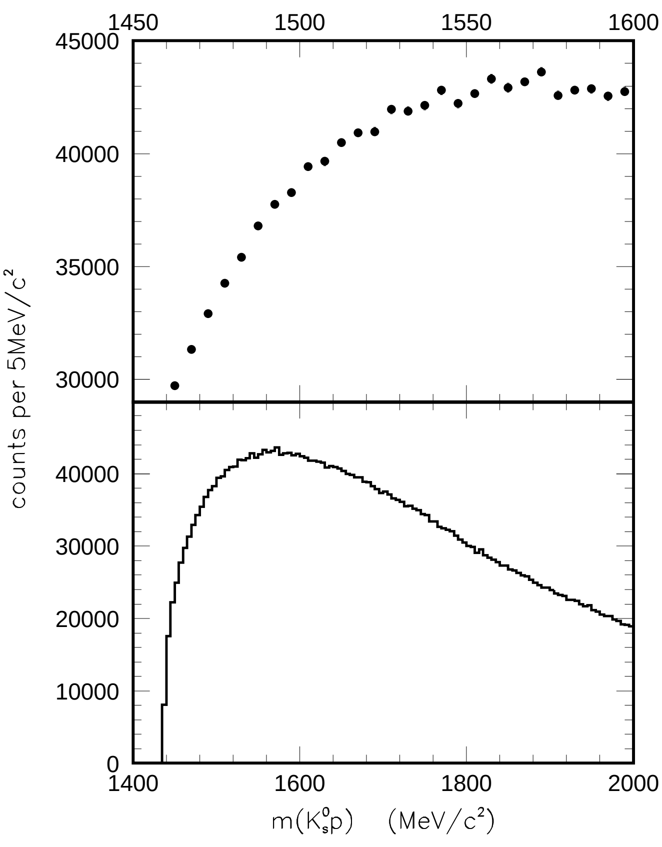


FIG. 3: Invariant mass spectrum of all observed $K^0_s p$ candidates. The upper plot shows an extended view of the region around 1540 MeV/$c^2$. The statistical errors are approximately of the size of the dots.

Upper limits on the $\Theta^+$ production cross sections were calculated separately for the copper and carbon targets, in bins of $x_F$ as listed in col. 1 of Table I. We used four mass windows of 20 MeV/$c^2$ width, centered at 1520, 1530, 1540 and 1550 MeV/$c^2$, resp., for $i = 1, 2, 3, 4$, thus covering the full range of reported values for the $\Theta^+$ mass. The width was chosen taking into account our mass resolution, $\sigma_m(K^0_s p) = 4$ MeV/$c^2$, and the reported values for the intrinsic width of the $\Theta^+$. The observed number of $K^0_s p$ combinations in each mass window is $n_i$. From a fit to the observed $K^0_s p$ mass spectrum between 1460 and 1700 MeV/$c^2$ we calculated the expected non-resonant backgrounds $b_i$. Upper limits $n_{max}$ on the number of $\Theta^+ \to K^0_s p$ decays were then obtained by the formula $n_{max} = max_i\{max(0, n_i - b_i) + 3\sqrt{b_i}\}$ and are listed in columns 2 and 5 of Tab. I. These limits have a confidence level of 99% and scale approximately with the square root of the width of the search window.

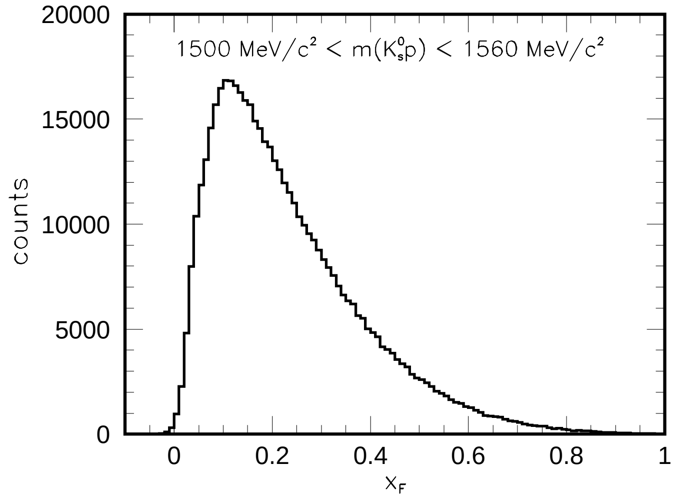


FIG. 4: $x_F$ distribution of for $K^0_s p$ pairs in the mass range 1500 MeV/$c^2$< $m(K^0_s p)$ <1560 MeV/$c^2$.

Upper limits on the product of $BR$, the $\Theta(1540)^+ \to K^0_s p$ decay branching ratio, and the differential production cross sections $d\sigma_A/dx_F$ *per nucleus* are given in columns 3 and 6 of Tab. I. Assuming the dependence of the cross section on the mass number to be $\sigma_A \propto \sigma_0 \cdot A^{2/3}$, where $\sigma_0$ is the cross section *per nucleon*, we finally obtained the limits on $BR \cdot d\sigma_0/dx_F$ in columns 4 and 7 of the table.

Limits on the integrated production cross sections $\sigma$ were calculated by summing quadratically the contributions $(d\sigma/dx_F) \cdot \Delta x_F$ in the nine individual $x_F$ bins. The results are $BR \cdot \sigma_A(x_F > 0.05) < 38$ and $<15$ $\mu$b per nucleus for the copper and carbon target, respectively. An extrapolation to the cross sections per nucleon yields the two values $BR \cdot \sigma_0(x_F > 0.05) < 2.4$ and $< 2.9$ $\mu$b per nucleon. Since these are statistically independent upper limits, we can combine them to obtain $BR \cdot \sigma_0 < 1.8$ $\mu b$ per nucleon for $\Theta(1540)^+$ production by $\Sigma^-$ of 340 GeV/$c$ in the region $x_F > 0.05$.

| $x_F$ | copper target $n_{max}$ | $BR \cdot d\sigma/\mathrm{d}x_F$ [$\mu$b] $d\sigma_A$ | $d\sigma_0$ | carbon target $n_{max}$ | $BR \cdot d\sigma/\mathrm{d}x_F$ [$\mu$b] $d\sigma_A$ | $d\sigma_0$ |
|---|---|---|---|---|---|---|
| 0.05 - 0.15 | 520 | 230 | 14.5 | 550 | 105 | 20.0 |
| 0.15 - 0.25 | 500 | 205 | 13.0 | 480 | 80 | 15.3 |
| 0.25 - 0.35 | 340 | 140 | 8.8 | 350 | 55 | 10.5 |
| 0.35 - 0.45 | 390 | 140 | 8.8 | 290 | 40 | 7.6 |
| 0.45 - 0.55 | 250 | 65 | 4.1 | 240 | 25 | 4.8 |
| 0.55 - 0.65 | 190 | 53 | 3.3 | 160 | 16 | 3.0 |
| 0.65 - 0.75 | 115 | 33 | 2.1 | 130 | 13 | 2.5 |
| 0.75 - 0.85 | 70 | 21 | 1.3 | 55 | 6 | 1.1 |
| $> 0.85$ | 35 | 11 | 0.7 | 45 | 5 | 1.0 |
| | | $BR \cdot \sigma_A$ | $BR \cdot \sigma_0$ | | $BR \cdot \sigma_A$ | $BR \cdot \sigma_0$ |
| | | 38 | 2.4 | | 15 | 2.9 |

TABLE I: Upper limits on yields and cross sections. BR denotes the $\Theta(1540)^+ \to K^0_s p$ decay branching ratio. $\sigma_A$ and $\sigma_0$ denote cross sections per nucleus and per nucleon, respectively.

For a comparison of our result to observations of or searches for the $\Theta(1540)^+$ we concentrate on hadronic reactions. It is interesting to note that all these experiments investigated the $K^0_s p$ decay channel, but only the SPHINX experiment searched in the $K^+ n$ decay channel as well. Four experiments have reported observations of the $\Theta(1540)^+$ [2, 8, 9, 10]. The COSY-TOF collaboration using a proton beam of 2.95 GeV/$c$ and a liquid hydrogen target, has measured a cross section $\sigma_0 = 0.4$ $\mu$b per nucleon for *exclusive* production in the reaction $pp \to \Sigma^+(K^0 p)$ [9]. This value is below our upper limit, but an exclusive production cross section that close to the reaction threshold cannot be compared to inclusive production cross sections at energies of several hundred GeV. The JINR propane bubble chamber group using a proton beam of 10 GeV/$c$ has measured a total production cross section $\sigma_{propane} = 90$ $\mu$b [10]. Again assuming a dependence of the cross section on the mass number as $\sigma_A \propto \sigma_0 \cdot A^{2/3}$, one obtains a production cross section $\sigma_0 = 3.8$ $\mu$b per nucleon, which is larger by a factor of 2 than our limit. The SVD Collaboration using a proton beam of 70 GeV/$c$ and a combined carbon, silicon and lead target, has measured a production cross section $\sigma_0 = 30$ - 120 $\mu$b per nucleon for $x_F > 0$ [8]. This is much higher than our upper limit in practically the same kinematic range. The DIANA collaboration using a $K^+$ beam of 0.85 GeV/$c$ and a Xenon bubble chamber has not measured a cross section [2].

Negative search results were reported from at least 11 experiments [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Out of these 6 experiments studied hadronic induced interactions [14, 15, 16, 17, 18, 19] Usually these collaborations have compared their $\Theta^+$ production limits with their $\Lambda(1520)$ observations, and have obtained limits below 3 % on the event or production ratio of $\Theta(1540)^+$ w.r.t. $\Lambda(1520)$. This we cannot do, although we do observe $\Lambda(1520)$ decays, because in our experiment two-body decay channels were suppressed in the trigger. We can, however, compare our result to the HERA-B result of $BR \cdot d\sigma/dy < 4$ - 16 $\mu$b per nucleon at 95% CL for $\Theta^+$ masses between 1521 and 1555 MeV/$c^2$, at rapidity $y_{cm} \approx 0$. This value corresponds to $BR \cdot d\sigma/dx_F <$ 30 - 120 $\mu$b per nucleon, to be compared to our result $BR \cdot d\sigma/dx_F < 12$ $\mu$b at 99% CL and for $0.05 < x_F < 0.15$ (this limit was obtained by combining the statistically independent carbon and copper target results).

If the $\Theta(1540)^+$ exists, as many experiments suggest, then the cross sections for $\Theta^+$ production in hadronic reactions at higher energies are surprisingly low compared to the production of hyperon resonances. This fact by itself could provide important information on the nature of the $\Theta(1540)^+$ .


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[32] At large $x_F > 0.8$ we do however observe a broad ($\Gamma \simeq$ 90 MeV/$c^2$) resonance like structure at a mass of $\simeq$ 1750 MeV/$c^2$ which is possibly related to known $\Sigma^*$ resonances. A detailed analysis of this structure will be presented in a future paper.